

Internal Wave Generation Processes at Deep-Sills in the Luzon Passage Tgi kqp'qh'vj g'Uqwj 'China Sea

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LONG-TERM GOALS

We are focused on understanding small-scale processes that influence the ocean's thermodynamic and dynamic properties on the sub-mesoscale (scales less than 10 km). This includes the enhanced internal waves generation and turbulent processes occurring in the Luzon Passage at the Lan-Yu and Heng-Chun ridges.

OBJECTIVES

The waters of the Luzon Passage are among the most energetic environments in the global ocean. Tidal currents as large as 0.8 m/s and strong stratification over the steep ridge topography give rise to internal wave generation, driving baroclinic currents. In addition, the Kuroshio Current often drives strong flow through the area. Not surprisingly, this environment supports exceptional turbulent energy levels distributed over full depth, leading to mixing between the South China Sea and Kuroshio water masses. Here, we present the first full-depth, direct measurements of turbulence along the Lan-Yu Ridge of the Luzon Straits over a spring neap cycle of tidal forcing. Data were collected on the east and west slopes of a ridge crest suggested by model results to be the site of exceptional baroclinic conversion of the barotropic tide. Measurements at each of these locations show that the strongest turbulence levels occur during the phase of the flood-ebb cycle when flow is in the downhill direction, indicating either hydraulic or slope convection processes. Our analysis shows very large turbulence levels, with dissipation rates reaching 10^5 W/kg at 1000-m depth, and depth-integrated dissipation rate levels reaching 1 W/m^2 . This implies that at least 10% of the locally generated baroclinic energy is dissipated directly before radiating away and suggests that local turbulent processes have considerable impact on the internal wave generation occurring at this region.

APPROACH

We conducted a study of the turbulence properties and velocity structure in the Luzon Passage, which is the location for very strong internal wave generation by tidal forcing. Specific sampling was focused at several sites along the Lan-Yu and Heng-Chun Ridges (Fig. 1). The work site is located between the moorings deployed on the IWISE pilot study (also shown in Fig. 1). Station

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locations are specified in Table 1. The “M” stations are located at the crest of the Lan-Yu Ridge, just south of the Batan Islands, roughly along the 1000-m isobath. The N2 station is along the Heng-Chun Ridge, near the center of the IWISE mooring array at the 1800-m isobath. Each station was sampled in a series of 36-hr intervals, where turbulence profiling and CTD/LADCP profiling were done on a quasi-continuous basis. Turbulence profiling was done using the autonomous Rockland Scientific VMP-6000 instrument system, called the Deep Microstructure Profiler (DMP hereafter), described in the next section.

Table 1 shows the station occupation history. M1 – M4 were each occupied twice, during opposite phases of the spring-neap cycle of tides (Fig. 2). A single station on the Heng-Chun Ridge (N2) was sampled during a 36-hr period before the final transit back to Kaohsiung.

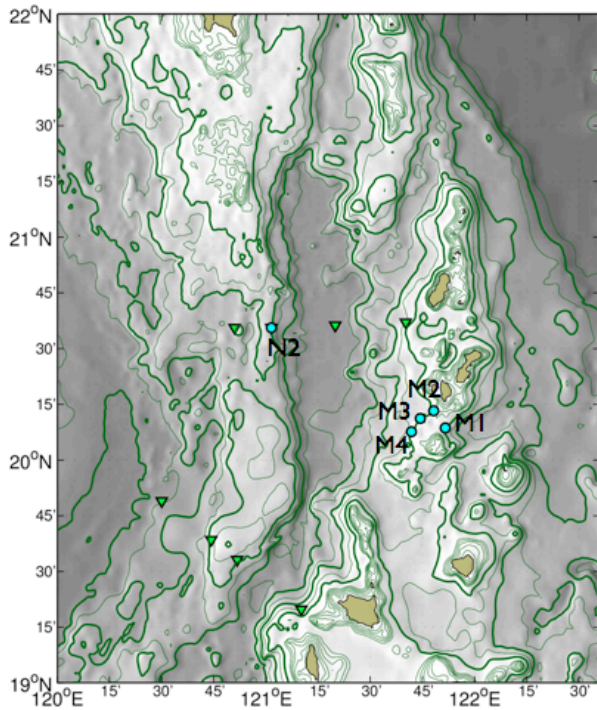


Figure 1. Map showing the Luzon Passage region. Bathymetry contours (1000-m increments) are shown, and indicate the relief of the Lan-Yu (eastern) and Heng-Chun (western) Ridges. Moorings locations used during the IWISE pilot study are depicted by green triangles. Stations used in our study are shown by blue circles. M1-M4 are on the Lan-Yu Ridge, and N2 is on the Heng-Chun Ridge.

Table 1. Nominal station locations and schedule

Station	occupation	t-start	t-end	lon	lat
<hr/>					
M1-1	22 June 2011 06:17	23 June 2011 15:21	121 51.649 20 08.635		
M2-1	23 June 2011 23:01	25 June 2011 08:59	121 47.692 20 13.173		
M3-1	25 June 2011 12:12	26 June 2011 22:30	121 43.519 20 10.804		
M4-1	27 June 2011 05:39	28 June 2011 12:46	121 41.394 20 04.078		
M1-2	28 June 2011 17:01	30 June 2011 03:10	121 51.599 20 08.640		
M2-2	30 June 2011 05:05	01 July 2011 01:58	121 47.214 20 13.333		
M3-2	01 July 2011 04:25	03 July 2011 00:36	121 44.560 20 11.514		
M4-2	03 July 2011 02:02	04 July 2011 14:03	121 41.424 20 04.207		
N2	04 July 2011 14:03	05 July 2011 00:31	121 06.947 20 30.332		

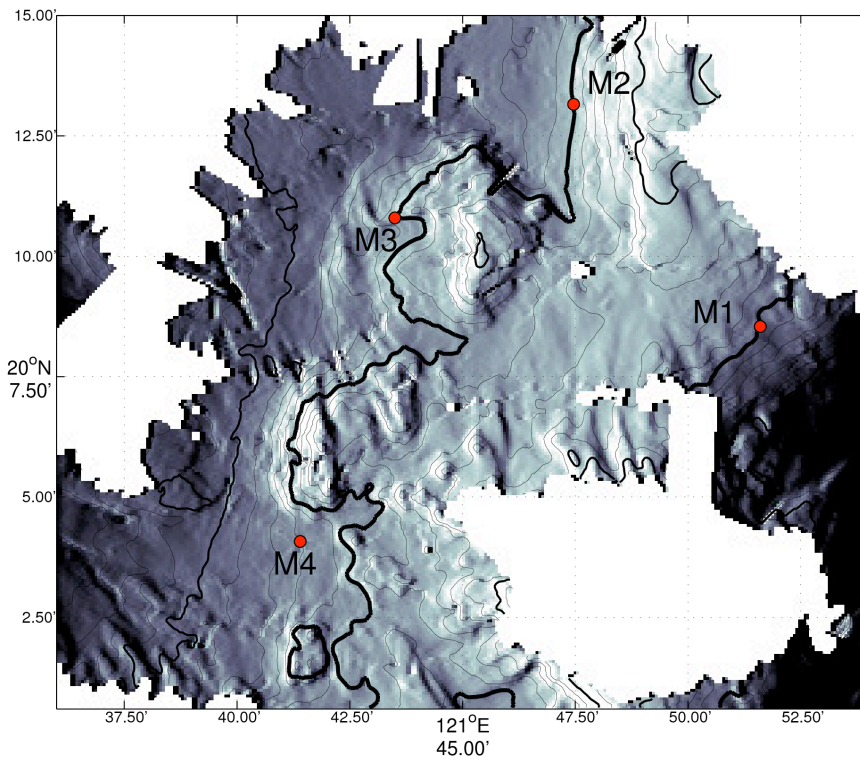
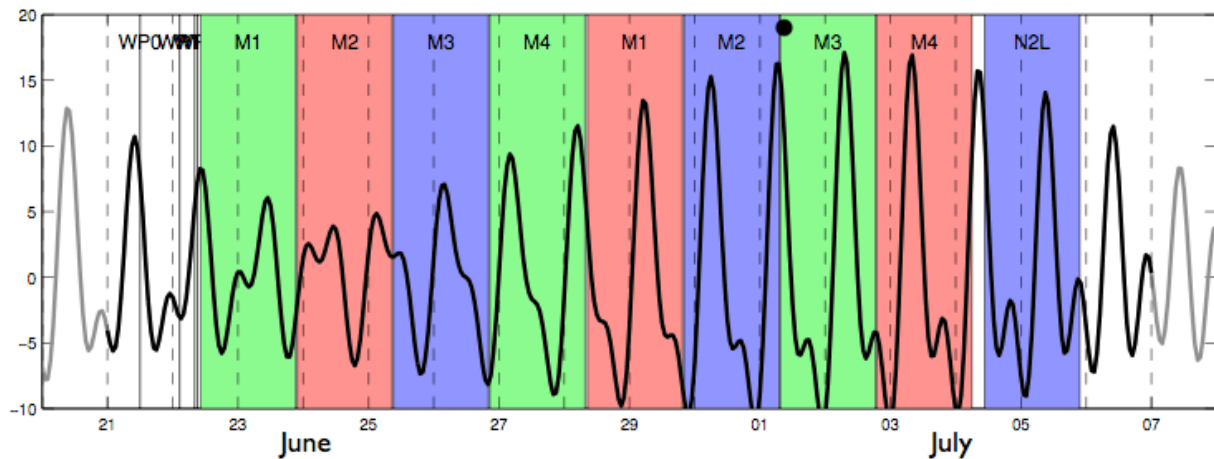


Figure 2. upper panel: Map showing the M-station site, with stations M1 to M4. Multibeam bathymetry is denoted by shading, with the 1000-m isobath contoured. Lower panel: time series showing the current speed in the Luzon Passage (in cm/s), with 36-hr time periods for each station indicated.



Turbulence profiler operations

The Deep Microstructure Profiler system (DMP) was used for measurements of turbulence during our survey. Measurements were typically made to within $O(100)$ -m of the seafloor. The profiler falls to the desired depth, drops one or two expendable iron weights (depending on the buoyancy configuration), and then rises back to the surface.

During the IWISE survey, we used two DMP instruments, unit 008 (known as Vito) and 010 (known as Vader). Vito is the original Rockland VMP-6000 system, and aside from critical

hardware upgrades to various components, is still running in its original configuration (lead acid battery). Vader was recently upgraded to have a lithium battery, and an improved pc core.

Both instruments were used in the opening days of the survey. Initially, Vito was equipped with a Benthos pinger, and Vader with an Xeos GPS iridium beacon. Both instruments were ballasted to fall at 0.75 m/s using two expendable weights. Vito was used for the first 3 profiles, at which point our desire to utilize the GPS beacon lead us to switch to Vader. The first 4 profiles with Vader occurred without incident, but on the 5th profile, the ship struck it during the recovery process.

Vito was then used for the next 45 profiles. Initially, it was used with the Benthos pinger with 2 drop-weights, but was later switched to the Xeos GPS beacon with 1 drop-weight. The latter configuration has a free-fall speed of 0.5 m/s.

During Vito's 48th profile (cast 008-053), the profiler failed to drop its weight at the specified depth and hit the sea floor. The micro-conductivity probe was badly bent, but the other probes were apparently unharmed. The system was recovered after coming to the surface 10 minutes late. Inspection of the system suggests that some aspect of the ASTP board (controlling the microstructure channels), or perhaps some aspect of the x-linux file system, became corrupted. Given the seriousness of the problem, Vito was suspended from service.

After a series of tests during the previous week, including several dip tests deployed on the rosette frame, the repaired Vader instrument case was setup with the foam and external frame from Vito. The system was deemed ready to be redeployed despite the risk associated with the bent bolts securing the internal frame to the bulkhead. Vader went into service during the final occupation of M3 (cast 010-006), and was used for 1-weight deployments with the Xeos beacon for the remainder of the cruise. The final 26 DMP deployments and recoveries of the cruise occurred without incident.

CTD, LADCP, and HDSS

The Revelle's CTD hardware was used extensively during the project, to make hydrographic profiles to full-depth along the Luzon Passage station locations. The rosette frame was equipped with an LADCP system consisting of RDI Doppler heads from OSU (up looking) and LDEO (down-looking). An OSU chi-pod was also used throughout the survey.

During the occupation of the N2 station, the CTD configuration was changed to horizontal, removing the CTD hardware from the path of the Doppler transmission. Also, and LDEO head was placed in the up-looking position.

The HDSS 50 kHz and 140 kHz sonar systems, as well as the RDI 75 kHz and 150 kHz systems, were operated at all times during the survey. The former was of significant value during the occupation of M1 – M4, as it produced estimates of flow over nearly the full depth.

Results

The M-station site was characterized by both strong stratification and strong currents, apparently due to the significant influence of the Kuroshio in the upper 400 m. Due to the Kuroshio, a persistent westward flow characterized the upper 400-m of the site. Tides are also very

significant, accounting for up to 2 knots of current at their maximum. Maximum *combined* currents reached 3 knots toward the west in the upper layer, at the new moon.

At all sites, turbulence levels at all sites were significantly enhanced over typical oceanic levels at all phases of the tide. Most of our effort was at the Lan-Yu, where our measurements span a spring-neap cycle (Figure 3). There, a clear increase in dissipation levels occurred during the spring tide period. However, large turbulence events occurred at all phases of the tide. The strongest turbulence event, as indicated by integrated dissipation levels (Fig 3., upper panel), was observed at station M1 (cast 010-005) just prior to the minimum period of neap tides.

In the case of the largest dissipation events, integrated dissipation levels reach over 1 Wm^{-2} , on the same order of magnitude as the baroclinic conversion occurring at the ridge. Of the dissipation events that reach over 0.5 Wm^{-2} at the M-station site, 4 of the 6 events occur during the time period just before the spring tide. An association between higher-frequency aspects of the tides, such as the diurnal and semidiurnal pulsing, with occurrences of higher dissipation, will be the subject of further investigation. Outbreaks of elevated dissipation clearly occur during instability events of the density field in the presence of high shear (see LADCP section). Thorpe-scale displacements of overturns at sites of high-dissipation were examined, and Thorpe scales reach O(100)-m in the largest cases. These overturns are extraordinary, given the highly stratified nature of the region.

At the N2 site, we sampled turbulence levels for 36-hrs, during the 3-4 day period after the new moon. This site is vastly different from the M-station site. The site is located on the Heng-Chun Ridge, at the 1800-m isobath. The upper-ocean current at this site was persistent to the north-northeast. As such, profiler and CTD deployments were done approximately 1 km south of the N2 mooring site, which generally resulting in profiler drift directly into the area of the mooring. Profiles were typically done to 1550-m depth, chosen to prevent collisions with the nearby ridge axis.

Measurements at N2 show a relatively quiet thermocline. Below 1200-m depth however, very large turbulence levels were observed often (Figure 4). These events seem to be associated with slope-convection, accompanied by very strong vertical velocities, though the details will need to be examined further. During one particularly large turbulence event (cast 010-027), the turbulence was so strong that the fall rate of the profiler slowed to 0.12 m/s, triggering the fall-rate release protocol, causing the profiler to drop weight prematurely at 1400-m depth. During our 36-hour occupation of the N2 site, we conducted a 3-hr yo-yo with the CTD to examine near-bottom processes contributing to turbulence. The LADCP record (Fig. 6) showed that large vertical velocities occurred during the convective outbreaks.

LADCP Data (A. Thurnherr)

The LADCP data were also processed for vertical velocities using the simple method described by Thurnherr (2011), which essentially consists in subtracting the vertical package velocity derived from the CTD pressure record from the corresponding ADCP velocity measurements. Significant improvements to the software were made during the cruise, although there remains an unexplained 3% vertical-velocity bias in all ADCPs used during the cruise that was empirically corrected for during processing. Fig. 5 shows a time-depth series of the vertical velocities from the partial-depth yoyo cast 142 near the bottom of the Kuroshio layer, suggesting that the high-

frequency internal waves, which are presumed to dominate the vertical velocities, are associated with small temporal and spatial scales. Fig. 6 shows the zonal (i.e. cross-ridge) and vertical velocities of the full-depth profiles 145-159 at location "N2" approximately 1.5km south of the IWISE moorings. Near the seabed there is a clear correlation between zonal and vertical velocities (up- and downslope flows), which appear phase-locked to the tide. Finally, Fig. 7 shows the vertical velocities from the partial-depth yoyo cast 160, also at the "N2" location. There is clear thinning of the downwelling layer near the seabed during the first 2 hours or so with a, presumably westward flowing, upwelling layer above. About 110 minutes into the cast, the downwelling layer thickens very abruptly. The patches of strong upwelling embedded in the downwelling layer observed near the end of the record are associated with strong vertical density variations (not shown), suggesting that they are active overturns.

CTD and HDSS Data

The analysis of Revelle's 50-kHz Hydrographic Doppler Sonar System reveals the strong signature of the Kuroshio. Stick diagrams (Fig. 8) show that the flow in upper 600 m is dominated by the Kuroshio Current at both the M-station site and N2. The flow below 600 m at station M1 has strong tidal residual current, oriented by the bottom topography. At station M1, the first occupation was near neap tide while the 2nd round occupation was approaching spring tide. The tidal residual currents have opposite direction in these two periods of observation. The details of the mechanisms at play in the deep currents require further analysis. At the last station, N2, the mean flow extending down to 800 m is also presumed to be of Kuroshio origin. The magnitude of the N2 mean flow is stronger than that at the M-station site.

The tidal currents in this region are very complicated (Fig. 9). There are numerous layers of sheared currents. A preliminary analysis of tidal current at station M1 suggests that the clockwise components of tidal current are comparable with that of counter clockwise, which suggests this is not a simple progressive wave. The vertical structure of tidal current shows that the semidiurnal component has mode-1 structure. The diurnal components of tidal current have higher mode structures.

The results of CTD data support the flow observations. The T-S diagrams (Fig. 10) suggest that the region is dominated by Kuroshio water, similar to those at the east of the Philippine Sea (PHS), especially during the flooding tide. There are some signatures in the T-S diagram suggesting that the upper ocean water-mass has mixed with water from the South China Sea (SCS) water during tidal ebb. The issue of deep water exchanges through the Luzon Strait has been studied for a long time. Wyrki [1961] showed that in the upper and intermediate layers of the SCS could be traced back to the Philippine Sea through the Luzon Strait. The T-S characteristics of deep waters of the SCS and the PHS are about the same at 1500–2000 m which indicated that the deep SCS is ventilated by water from the PHS passing over the Luzon Strait.

Data Sharing Schedule

A copy of all cruise data was made available to the Philippine observer on the vessel at the conclusion of the cruise. Data from the project is also available to IWISE investigators at the discretion of the US sponsor (ONR).

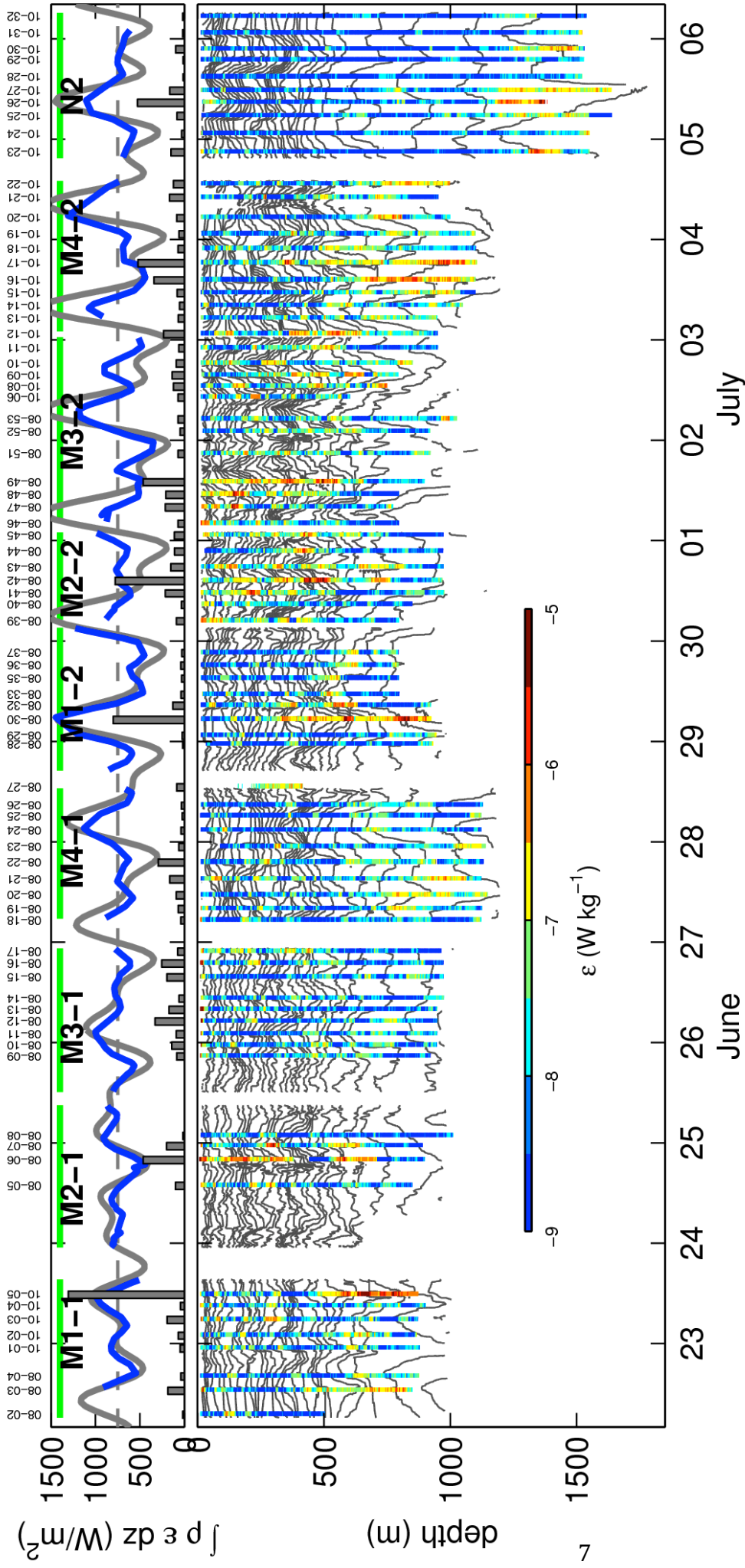


Figure 3. Summary plot showing the entire DMP time-series, including temperature from the CTD, and dissipation rates from the DMP. The upper panel shows TPXO tidal U in Luzon Passage (grey) and the measured depth-mean LADCP U (blue). Integrated dissipation levels, are indicated by the bar graph. Station names and cast numbers are also specified. Green bars indicate the station occupation periods.

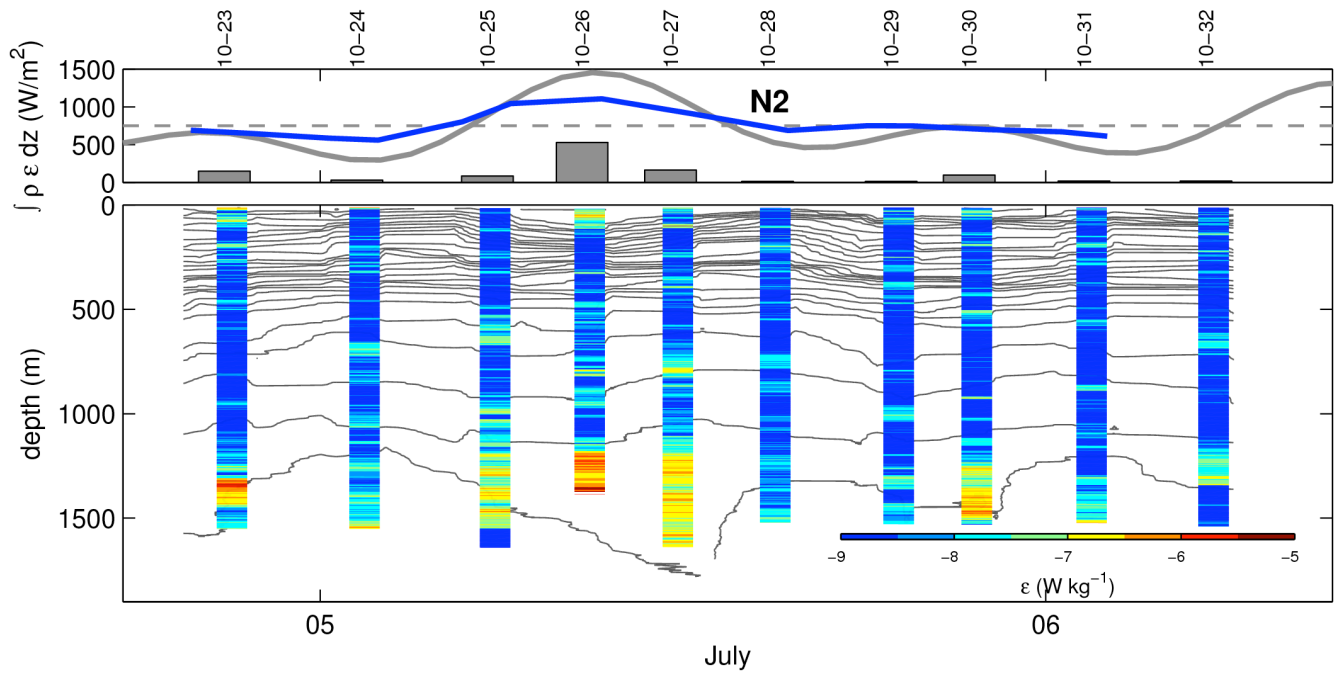


Figure 4. Time series showing CTD and DMP data at the N2 station site. Details as in Fig. 3.

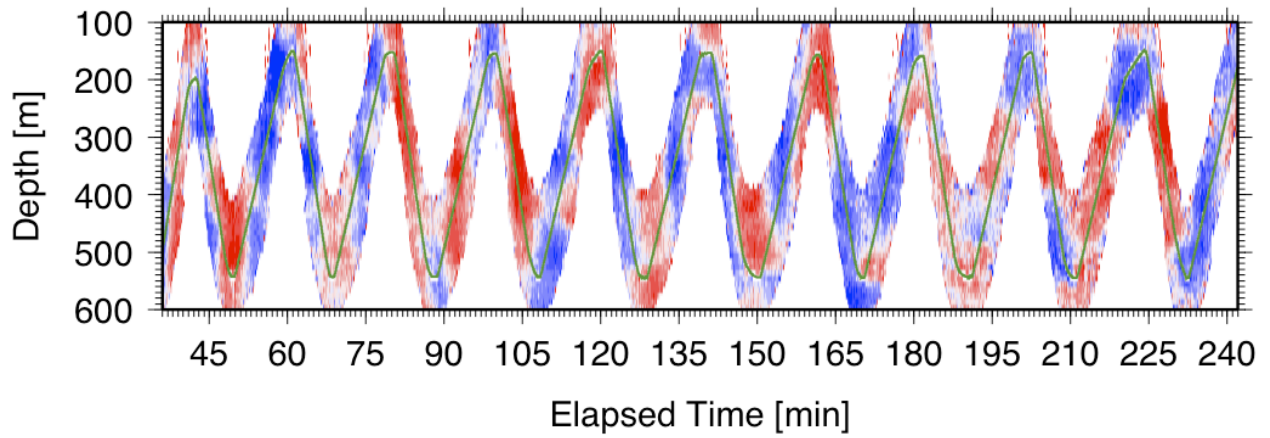


Figure 5. Vertical velocities observed during yoyo station 142 at the bottom of the Kuroshio layer. Red/blue indicates up-/downwelling respectively. RMS velocities at each depth are 4-5 cm/s.

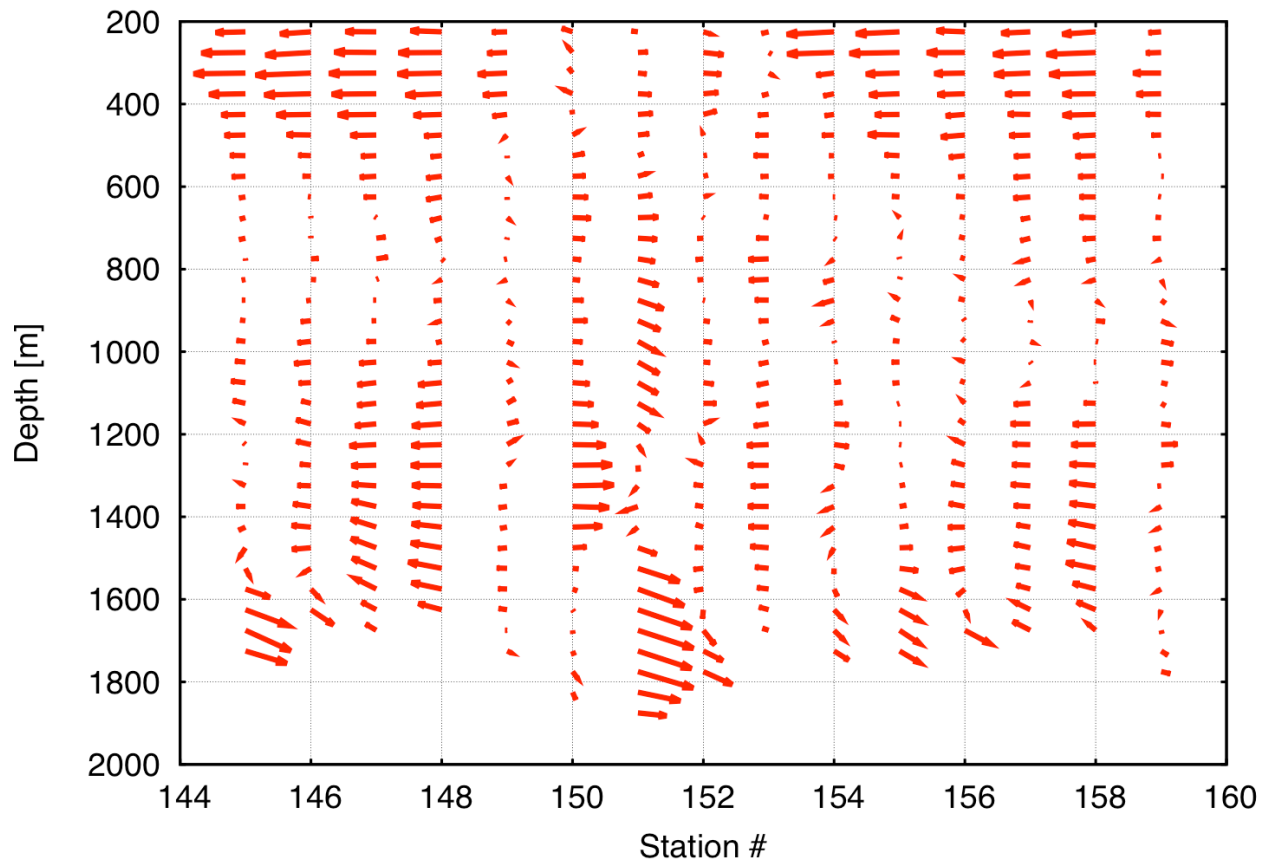


Figure 6. Zonal and vertical velocities observed in full-depth profiles at location N2 in 50m bins. Peak velocity at station 151 is 85cm/s to the east and 23cm/s downward at 1675m.

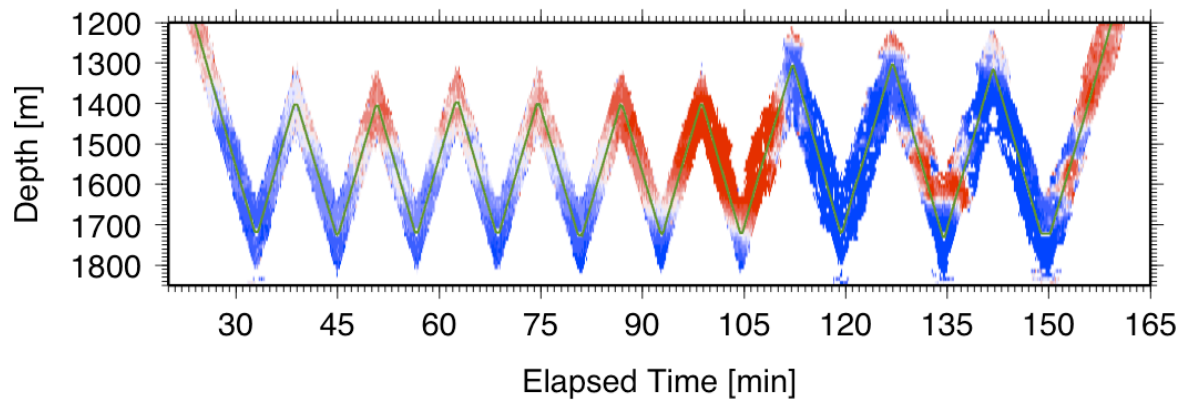


Figure 7. LADCP yo-yo at the N2 site, station 160 near the seabed. Red/blue indicates up-/downwelling respectively. Red-blue color map indicated vertical velocity from +30 cm/s (red) to -30 cm/s (blue). RMS velocities at each depth increase from 10cm/s at 1400m to >20cm/s at 1800m. Strong vertical velocities were associated with near-bottom slope convection events. This patches were accompanied by very large dissipation levels.

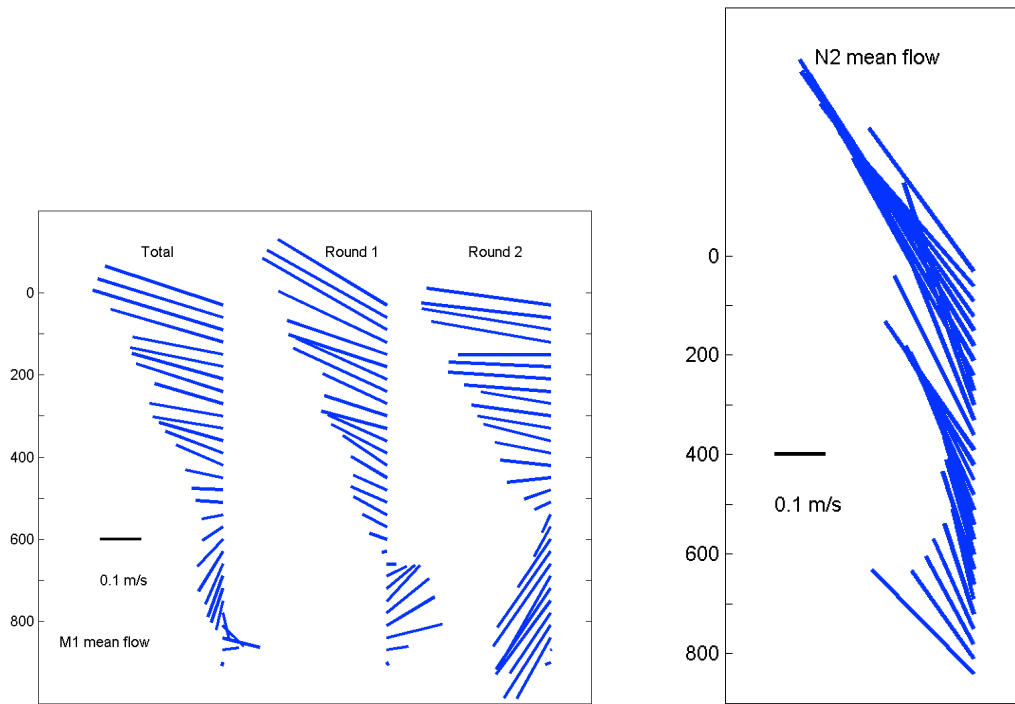


Figure 8. Stick diagram of mean flow at station M1 (left) and N2 (right)

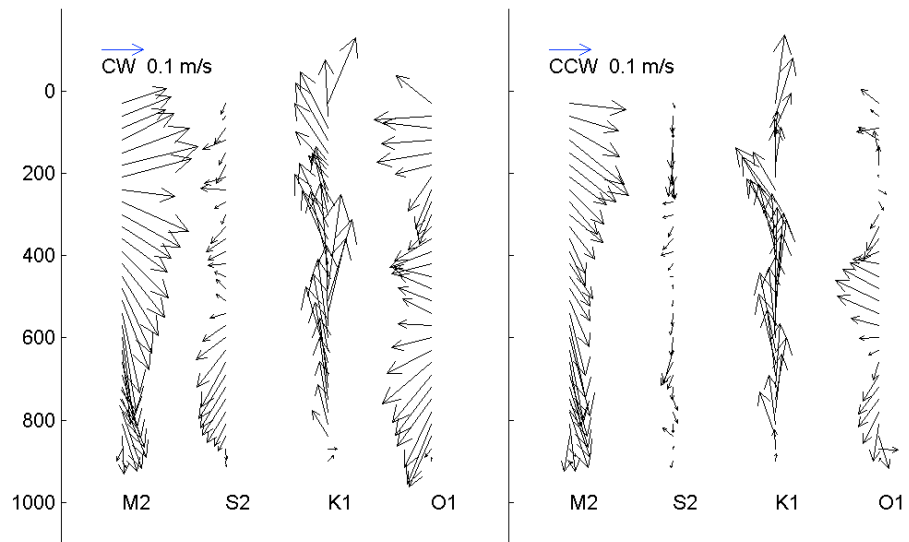


Figure 9. Decomposition of tidal current at station M1 suggests that the clockwise components (left) are comparable with that of counter clockwise. The y-axis is the water depth in meters. Note that the direction of the stick is the phase and the magnitude of the flow is indicated by the upper-left arrow.

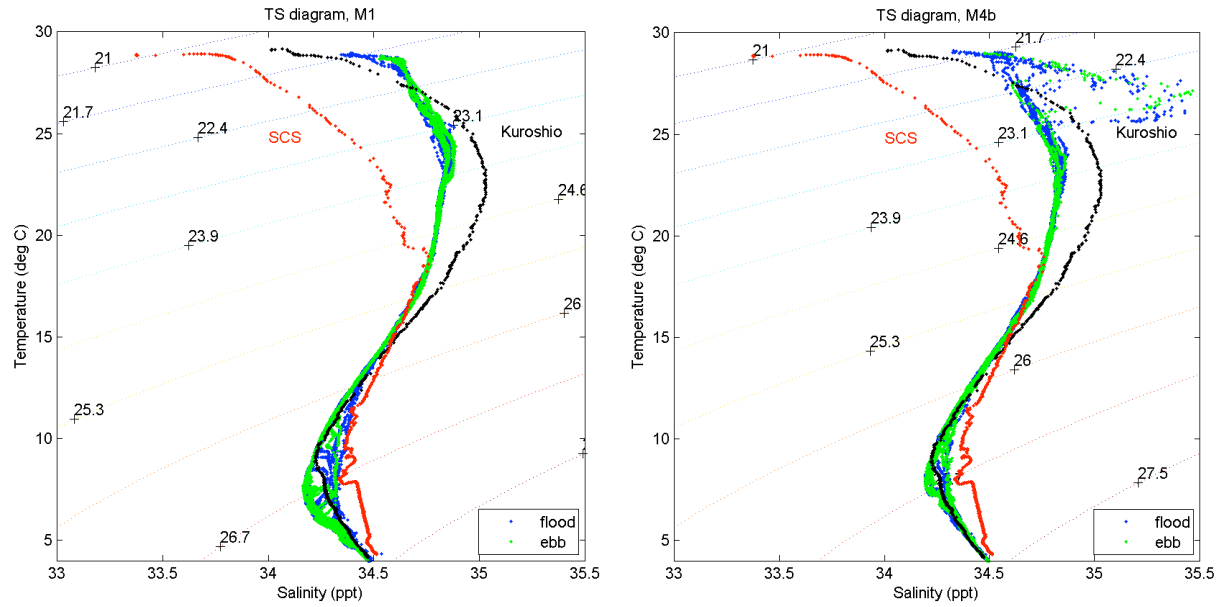


Figure 10. T-S diagram of CTD observations at stations M1 (left) and M4 (right). The typical water of SCS (red) and PHS (black) are plotted for reference. The green is during the ebb tide while blue are flood. The surface waters are all of Kuroshio origin, with some fresh water input from rain in the past weeks due to TS Haima and TS Meari. The bottom water of during ebb indicates strong signature of mixing with SCS water.